Visualizing Planetary Spectroscopy through Immersive On-site Rendering

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Abstract

Remote sensing is currently the primary method of obtaining knowledge about the composition and physical properties of the surface of other planets. In a commonly used technique, visible and near-infrared (VNIR) spectrometers onboard orbiting satellites capture reflectance data at different wavelengths, which in turn gives insight about the minerals present and the overall composition of the terrain. In select locations on Mars, rovers have also conducted up close in-situ investigation of the same terrains examined by orbiters, allowing direct comparisons at different spatial scales. In this work, we build *Planetary Visor*, a virtual reality tool to visualize orbital and ground data around NASA's Mars Science Laboratory Curiosity rover's ongoing traverse in Gale Crater. We have built a 3D terrain along Curiosity's traverse using rover images, and within it we visualize satellite data as polyhedrons, superimposed on that terrain. This system provides perspectives of VNIR spectroscopic data from a satellite aligned with ground images from the rover, allowing the user to explore both the physical aspects of the terrain and their relation to the mineral composition. The result is a system that provides seamless rendering of datasets at vastly different scales.

We conduct a user study with subject matter experts to evaluate the success and potential of our tool. The results indicate that Visor assists with geometric understanding of spectral data, improved geological context, a better sense of scale while navigating terrain, and new insights into spectral data. The result is not only an immersive environment in a scientifically interesting area on Mars, but a robust tool for analysis and visualization of data that can yield improved scientific discovery. This technology is relevant to the ongoing operations of the Curiosity rover and will directly be able to represent the data collected in the upcoming Mars 2020 Perseverance rover mission.

Index Terms: Spectroscopy—Remote Sensing—Vitrual reality

1 Introduction

Planetary remote sensing is the study of planetary bodies through observations made at a distance, typically by a spacecraft in orbit or performing a flyby. Planetary geologists use remote sensing to study the surfaces of other worlds, enabling them to piece together geologic histories and learn about potential habitability. Planetary scientists are studying surfaces they will never set foot on, which presents unique challenges not encountered by terrestrial geologists. Advances in data visualization and integrated analysis tools have therefore been of outsized importance in the field. The ability to accurately localize and understand spatial relationships between geologic features is vital to planetary scientific analysis. Remote sensing from satellites can be used to obtain information about a planetary surface's albedo, composition, morphology, and thermophysical properties. In a common technique, visible and near-infrared (VNIR) imaging spectrometers onboard orbiting satellites measure light reflected from planetary surfaces across a range of wavelengths, represented by an image cube. These spectra can be compared with laboratory spectra of known materials on Earth to identify spectral features that are diagnostic of specific minerals in rocks and soils. VNIR spectroscopy has resulted in major breakthroughs in the understanding of Martian geologic history, including its record of aqueous alteration and potential for habitability e.g. [6, 14, 34, 36].

Mars is also one of few planetary bodies that have been explored in situ[1] by robots. Four NASA rover missions have been sent to Mars to date, with a fifth scheduled to land in February 2021. NASA's currently active rover mission, the Mars Science Laboratory Curiosity (MSL) [24], has sent back thousands of images of the Martian surface since its landing in 2012. Rover missions like MSL can acquire data at the mm-to-m scale, a difference of many orders of magnitude compared to orbital VNIR data. These include image mosaics that form 360 degree panoramas, localized target imaging, and long-distance imaging that together build up a rich landscape around the rover traverse. However, the precision data is limited to locations and paths where the rovers have travelled, lacking the contextual information of nearby terrain.

We create Planetary Visor, a visualization tool that can synchronize coordinate spaces shared amongst orbital and in situ scientific instruments, opening opportunities for more efficient analysis and dissemination. This is accomplished by combining data captured from scientific orbital instruments such as the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) [33] and in situ data captured from the Curiosity rover.

1.1 Orbital Remote Sensing with CRISM

CRISM is a hyperspectral imager on the Mars Reconnaissance Orbiter (MRO). CRISM captures reflected and emitted light from the surface and atmosphere of Mars through two detectors covering 0.4 µm-1.0 µm and 1.0 µm-4.0 µm with 6 nm spectral resolutions. The wavelength region corresponds to the VNIR. CRISM is a push-broom spectrometer, acquiring each image line-by-line in the along-track direction of the spacecraft. In targeted modes, CRISM images

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[1]In planetary science contexts, *in situ* refers to observations made in close proximity to the targets, e.g. by landers or rovers, as opposed to by remote spacecraft or telescopic observations.

have a spatial resolution of 18-36 m/pixel.

CRISM data can be used to identify a broad range of minerals including silicates, oxides, salts, clays, and carbonates. Mapping of these minerals is used in concert with other datasets, namely higher resolution visible images, to make interpretations about the geologic history of the Martian surface. CRISM has provided key information for selecting Martian landing sites [19, 22, 23] and informing rover path planning [16, 18].

Each CRISM image has an associated Derived Data Record (DDR) file that contains ancillary information about the observation. DDR files have the same number of rows and columns as the main file, and each band encodes a different related property. Key bands in the DDR included latitude, longitude, elevation, slope, and slope azimuth, and incidence, emergence and phase angles.

1.2 In Situ Sensing with the Mars Science Laboratory

The MSL Curiosity rover landed on the surface of Mars in 2012. Its destination was the floor of 154 km diameter Gale Crater, and its goal to ascent the 5-km high interior mound, Aeolis Mons or Mt. Sharp. The two pairs of Navigation Cameras [31], located on the rover mast, capture stereo images of the Martian surface and are heavily used in navigating the rover. Curiosity also carries science cameras to capture both fine scale rock textures and context images of the terrain. Mastcam consists of a pair of color cameras with different focal lengths [4] that provide multispectral information from 0.4-1 micron. Multispectral Mastcam partially overlaps in wavelength with CRISM data. Another camera on the end of the robotic arm, the Mars Hand Lens Imager (MAHLI) [13], captures surface textures of rocks and soils.

Several other instruments on the payload measure chemistry or mineralogy by other techniques. The Alpha Particle X-Ray Spectrometer (APXS)

1.3 Current Challenges with Visualization

The scientific return of CRISM and the Curiosity payload are highly complementary. CRISM data is used to select landing sites with interesting mineralogy, enabling high scientific output from rovers such as Curiosity. Thereafter, chemistry and mineralogy observed with Curiosity informs interpretations of orbital data for the vast majority of the Martian surface that remains unexplored by rovers. In several instances, rover results have agreed well with mineralogy observed from orbit [16, 17]. However, instruments on the ground observe from a fundamentally different perspective than orbiting instruments. The spatial scales observed differ by many orders of magnitude, and the methods of measuring mineralogy vary. To make correlations between such disparate datasets, a precise understanding of their location in 3D space is key.

Many challenges currently exist in visualizing these environments as a whole. Existing GIS software (e.g. ArcGIS, ENVI) cannot effectively join small scale and large-scale 3D data in a single environment. The JPL visualization tool for Curiosity, OnSight [1], incorporates very limited orbital imagery and, more importantly, is not available to the public. It is challenging to precisely localize CRISM data in the context of Curiosity observations that are several orders of magnitude higher resolution and yet correspondingly smaller in their spatial coverage. The user can find it difficult to maintain a sense of scale without familiar spatial references. Finally, in order to appreciate trends over large distances, users are currently forced to merge many datasets locally, which entails significant resource investment in both time and data storage.

1.4 Planetary Visor

To address the challenges of visualization mentioned in §1.3, we present Planetary Visor. With the Visor tool we demonstrate the integration of CRISM hyperspectral imaging data with Curiosity images and data (§3.2), as shown in Figure 1. However, our system

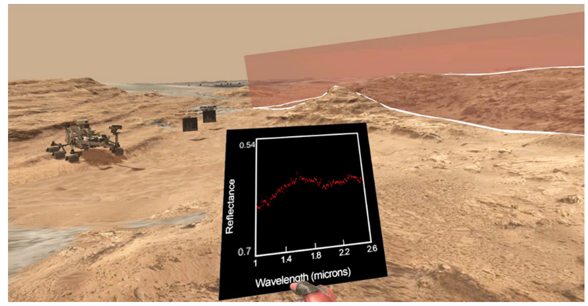

Figure 1: The red mesh is our visualization of a pixel acquired by CRISM, a reflectance spectrometer onboard the Mars Reconnaissance Orbiter. The bottom of the pixel is outlined in white to clearly mark its intersection with the terrain. In the center is a spectral plotter, where the spectrum of the area covered by the pixel is plotted. The user is therefore able to visualize orbital and in-situ data in a single environment with accurate localization and scaling.

can be extended to other datasets and planetary terrains. Our system visualizes a CRISM pixel footprint as a three dimensional shape, superimposed on a terrain constructed from high-resolution rover datasets in §4.1. This approach provides a new perspective and can potentially give scientists insight about the pixel's true shape, size and intersection with the surface. To support scientific analysis, we equip the user with controls for efficient and intuitive navigation through the data in §4.2. This includes interfaces for comparing and averaging multiple spectra across the terrain at multiple scales of comparison.

We design the implementation of our system to be maintainable and extensible with platform-independent abstractions through the Unity Game Engine. The system is cross-platform across SteamVR and Oculus headsets, and can also run with mouse/keyboard on desktop. The system includes the ability for planetary scientists to extend the tool to incorporate their own orbital datasets and terrain models. Finally, we conduct a user study with eight planetary scientists to understand the benefits of the tool in professional scientific workflows §5.

2 Related Works

In this section, we review related works in planetary data visualization and immersive scientific visualization.

2.1 Planetary Data Visualization

2.1.1 2D Planetary Data Visualization

Earth and planetary scientists use a variety of desktop applications to visualize satellite and field work images. Some of these applications are exclusively for visualizing and analyzing Earth data (Google Earth [21], NASA Worldwind, Planet, and more). Other applications such as ENVI, ArcGIS, and JPL's NASA Mars Trek [29], can be used to visualize and analyze planetary data. The Java Mission-planning and Analysis for Remote Sensing (JMARS) [11] provides mission planning and data-analysis tools that are widely available to NASA scientists, instrument team members, students and the general public.

Some of these tools, including ArcGIS and ENVI, give users the capability to display digital elevation models in 3D. These representations are limited by screen size and can be slow and difficult to manipulate. Although these are effective for some tasks, they do not provide immersive experiences or the ability to support tasks involving 3D comparisons.

Images from Curiosity's instruments are typically viewed in 2D or as anaglyphs using red-blue glasses. Without familiar reference points, estimating size and distance can be difficult in 2D views.

2.1.2 Virtual Reality for Planetary Data Visualization

Virtual reality can offer perspectives that overcome the limitations of 2D visualizations, e.g., object occlusion [5]. Immersion into the data enables users to make better spatial judgements and see details that were not clear in the 2D visualization [15]. Depth and distance estimation have been found to be more accurate when performed in 3D environments compared to 2D image based tasks [8, 28, 44] especially with depth cues [35].

Virtual reality is utilized as a tool to improve visualization [7, 9, 41], and assist in dissemination of planetary data [9, 30]. Immersive environments have been especially useful in Mars science around mission planning [37, 43]. The Autonomy and Robotics Area (ARA) at NASA Ames Research Center [12] has also experimented with virtual reality to control complex robotic mechanisms.

OnSight [1], developed by the Jet Propulsion Laboratory, is a tool for visualizing data from the MSL mission. It displays meshes created from Navcam and Mastcam data in an augmented reality environment. Using the Microsoft Hololens, users can teleconference in AR and see other users' avatars in the environment. OnSight offers the ability to make annotations, see targets and teleport between locations. However, OnSight does not include any chemical or mineralogical data. It uses orbital images from HiRISE only as a backdrop to MSL images. Moreover, only a small demonstration environment is available to the public; the full tool can only be used by those who are officially members of the MSL team, severely limiting access.

Globe Browsing [7] addresses the difficult process for acquiring large amounts of scientific data, especially for non-experts, and the visualization and communication challenges of planetary data. Their solution integrates different visualization methods to create a navigable 3D environment in which scientists can effectively communicate discoveries. Although they make use of large dataset navigation and rendering techniques, Globe Browsing does not offer a visualization method that enables scientific analysis for aggregate datasets.

Open Space [9] – extended from Globe Browsing's API – is modular, allowing developers, scientists, and science communicators to tailor OpenSpace to their needs, import their own datasets and share interactive sessions. Open Space targets data variety, including multiple spatio-temporal scales, collaboration capabilities, visualizing satellite imagery, data from space probes, and position of celestial bodies.

VRGE: An Immersive Visualization Application for the Geosciences [25] enables color coding of volumetric data. The tool focuses on annotation and graphical overlays, rather than quantitative data.

2.2 Virtual Reality in Scientific Visualization

Virtual reality has shown to be useful across various applications of scientific data visualization such as astronomy [40], biology [32], cosmology [3], paleontology [38], robotics [12], analytics [42] and more. The 3D immersive environment recreates the environment of experimentation, allowing the scientist to collect data in a similar way to how the original data was collected [26]. Virtual reality in scientific visualization [10] explores different visualization techniques used in the field, and outlines problems with existing technology.

Comparison techniques utilized in "Spatial 3D and 4D data visualizations: A survey and future directions" [27] review the usefulness of 3D and 4D comparative visualization techniques such as juxtaposition, superimposition, interchangeability, explicit encoding, and combinations of these. Although they note that combinations may be the most effective in general cases, they identify superimposition as the best method to perform detailed spatial data comparisons. Additionally, they mention that the superposition technique is the preferred method to display multiple datasets that are simultaneously visible, spatially co-registered, and preserve all data. Since superposition can cause occlusion, we make the overlay transparent.

At the core of our approach lies the gathering of surface image data and the overlapping VNIR spectroscopy data. We hone in on the shaping and projection of pixels from CRISM, superimposed on terrain models generated from rover imagery. The result is a visualization that encompasses datasets at multiple scales and their intersections, in a way that enables investigators to make comparisons with little burden.

3 Shape and storage of planetary data

3.1 Spectral data cube format for spectral pixels

As MRO flies over a target, CRISM points its gimbal at the target and collects a line of spectral data samples. As the spacecraft and gimbal move, multiple lines captured in the along-track direction are built up into an image. These lines of spectral data are stored in a *spectral data cube* format. Each spectral reading is stored in raster scan order, indexed by x (where on the line the sample is), t (the time the line was captured), and λ (the spectral wavelength). These readings form a spectral data cube. The image cube also comes with an associated derived data record (DDR) file that includes the (planetocentric) longitude and latitude of each pixel in the image cube.

CRISM data cubes are accessible through NASA's Planetary Data System (PDS) Geosciences Node, which archives data derived from NASA's missions to planetary bodies, including images, chemical and mineralogical data, and derived products. Users can also prepare and export their own spectral data cubes and associated DDR from their traditional GIS tool, and import it into Planetary Visor. This allows the planetary scientist to use datasets that have been processed differently (e.g., with different atmospheric corrections) and to align the data to precisely (or imprecisely) fit the cartological placement of the CRISM data according to their preferred methodology, (e.g., correction and/or performing tiepoint analytics to combat the uncertainty of remote measurement).

3.2 Shape of a pixel footprint

Though image pixels on a map are typically imagined as being square, the shape of the spectral pixel samples as they reach the surface takes a different shape, as shown in Figure 2. Rather than a simple image projection, this shape is determined by the position of CRISM and MRO as their sampling line sweeps over the terrain, controlled by a gimbal.

To represent the area of geological features that are captured by each pixel, we represent the shape of a pixel in 3D, which gives visual insight about the pixel's intersection with the terrain, and the contents within it. The 3D projection of the shape of a pixel provides more insight into the relationships between physical and compositional features, than that of a 2D shape, according to our user responses. Additionally, the 3D shape reveals how properties such as slope angle, aspect, and rock texture might be affecting the spectral signal.

Calculated from spacecraft instrument positioning relative to the planet surface, the DDR provides the center location of the footprint of each pixel as it lands on the ground, which traces the pointing trajectory of the spectrometer's pixel to the surface. We approximate the edges of the pixel footprint to be halfway towards the centers of the neighboring pixel footprints. Then, we assume that the edges and corners of the pixel on the ground follow a solid angle that points to the overhead CRISM's location, whose position can be accessed through SPICE records obtained from NASA's Navigation and Ancillary Information Facility (NAIF).

To make clear the shape of a pixel and the terrain it covers, we outline the bottom of the shape in white, as shown in Fig. 1. However, it is worth noting that the precise placement is subject to multiple forms of uncertainty, including from instrument pointing error and topographical misalignment. Planetary scientists often "correct" for this by providing tie points to align spectral data with a basemap.

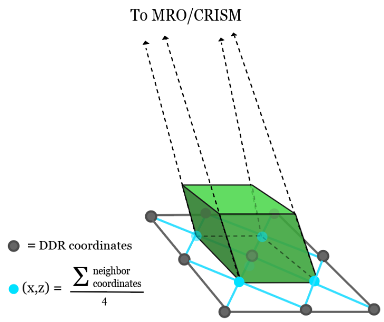

Figure 2: The shape of a pixel is defined by the location of MRO when the image was acquired and the shape of the terrain. Our system uses the 3D environment to represent spectral pixels as polyhedrons that point in the direction of the satellite. We determine the corners of the PixelBlock by averaging the four neighboring DDR coordinates.

Visor can use the corrected/aligned spectral data as its source or the uncorrected raw spectral data. Future efforts will investigate the potential visualization of the uncertainty associated with the data, as well as tools to improve the tie point alignment procedure. The resulting visualization of the shape of a pixel and its intersection with the ground can assist planetary scientists with the geometric understanding of their spectral data.

3.3 Terrain Landscaping from Rover and Orbital Data

An understanding of the shape of the landscape through topographic modeling is crucial to mission planning and scientific analysis. The visualization of planetary terrain gives scientists information about the geospatial features and landforms, giving them insight into natural events. In-situ instruments, such as the cameras on the Curiosity rover, can be used to capture rich views of the terrain for navigation purposes and/or scientific return. Through computer vision techniques, e.g., photogrammetry and stereo vision, these images can be transformed into 3D virtual environments. We leverage Agisoft Metashape [2] and an open-source NavCam-based Blender project [39] to synthesize terrain from rover imagery. Publicly available photogrammetric meshes [20] can also be integrated into the virtual environment. The resulting terrain is a combination of multiband (color) Mastcam images where available supplemented by more plentiful monochrome Navcam data. We use data from the HiRISE camera, also onboard the Mars Reconnaissance Orbiter to anchor the local meshes and expand the user's environment beyond the relatively narrow radius of the rover's view around its traverse. A HiRISE Digital Terrain Model (DTM) mosaic (1m/pixel) is draped with a HiRISE single-band data mosaic (0.25 m/pixel). By loading such environments into game engine software, we can allow users to virtually traverse the terrain through desktop and virtual reality interfaces, and position 3D scientific overlays onto the terrain.

We access rover data using the Analyst's Notebook tool hosted by the PDS Geosciences Node. Curiosity Rover data is downlinked to Earth using a satellite relay and the Deep Space Network. After a period of exclusive science team access (typically a few months), they are permanently archived by the PDS.

Data is organized by sol (a Martian day, approximately 24.6 hours, and the typical cadence of Curiosity rover operations). The quantity of data returned reflects the challenges of balancing available power, time, and competing priorities during planning as well as the available downlink volume. As of January 2020, Curiosity has driven over 24 kilometers. The quantity of imaging data along the traverse varies dramatically. Some locations along lengthy drives have sparse imaging data available. Others, in which the rover sat in place for many sols or conducted a "walkabout" crisscrossing a small area may have hundreds of overlapping images. Altogether, this creates a varying quality of terrain models in our software, depending on available data.

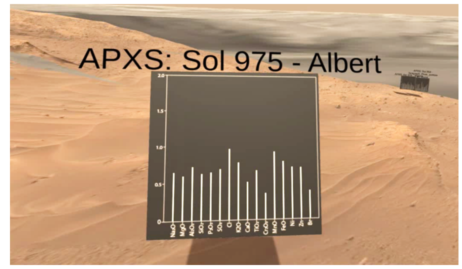

Figure 3: Screenshot of APXS charts placed at capture location. The x axis shows measured elements and oxides, and the y axis is a ratio to a standard observation. Auxiliary information provided includes the target name and sol number on which it was acquired. The integration of the APXS dataset allows in-situ chemistry to be compared to orbitally-derived mineralogy from CRISM.

3.4 APXS Data

An early request of our planetary scientist collaborators was to juxtapose APXS data, rover-based data which measures the chemical makeup of the rocks and minerals on the surface. These data are presented in the form of quantities of elements and oxides present in the sample. To allow the user to better understand chemistry of the rocks and soils, as well as their relation to the terrain, we visualize the APXS data at the location at which the sample was taken, as shown in Figure 3. The data are represented as a simple bar chart of the oxides and elements ratioed to a standard observation. The data is presented on "billboards" that continually turn to face the user at all times to reduce perspective issues.

4 System Design

In this section, we describe how our system visualizes orbital data with ground views in a unified immersive environment. Data acquired by CRISM and the Curiosity rover share physically overlapping footprints. Combining these datasets provides a bridge between these two complementary perspectives to help scientists study the properties of planetary surfaces. To this end, we aim to develop interactive scientific tools to unify the visualization and understanding of such data. While other techniques do portray these datasets, e.g., GIS-based map visualizations, no single tool exists to unite orbital and in situ datasets with proper scale and localization of remote sensing pixels.

To this end, our Visor system incorporates:

- *PixelBlock*, a 3D visualization to represent the spatial footprint of a spectral data sample as it intersects with the terrain, paired with the corresponding spectral reading.
- A set of interactive tools to assist with scientific analysis through visualization, selection, and manipulation of spectral data.
- A navigable 3D environment for desktop or virtual reality use for immersive exploration of the planetary data.
- A virtual reality visualization and interaction technique for making simultaneous comparisons of orbital and ground data.

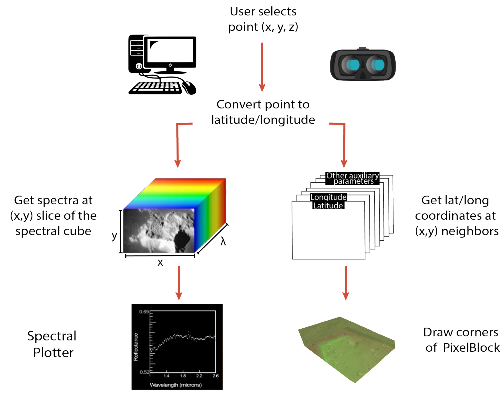

Figure 4: Overview of the process of plotting spectra for a PixelBlock selection. The input is an x,y,z coordinate from desktop or VR, which is translated to the planetocentric latitude and longitude, which is then used to locate the nearest row/column indices of the DDR and spectral data cube. Those indices are used to access pixel geometry in the DDR to draw the PixelBlock (Section 4.1), and access samples from the spectral data cube to plot spectral reflectance (Section 4.2.1).

4.1 PixelBlock Spatial Visualization

The PixelBlock is an interactive virtual object that visually conveys a spatial positioning of orbital instrument data among in-situ ground-based data, despite the data having been acquired by different scientific instruments at different scales. As mentioned in Section 3.2, CRISM pixel footprints are not accurately represented as squares or cubes, as CRISM scans from different angles and distances above the surface. The PixelBlock accounts for this by generating a dynamic polygon mesh, shaped by the angle of incidence from the MRO's location.

To generate the PixelBlock, Visor receives user input to generate a spectral plot and the mesh geometry of the PixelBlock, as illustrated in Figure 4. To select a spectral sample, the user points their mouse or VR controller at the terrain. The system uses a 3D raycast to identify the intersection with the martian surface. Visor translates the collision point of this intersection in the virtual environment x,y,z coordinates to Martian planetocentric latitude-longitude coordinates. The system then searches the DDR for the nearest latitude and longitude pair. The row/column indices of this pair are used to access the appropriate sample from the spectral data cube. The neighboring points in the DDR are used to generate the 4 corners of the PixelBlock, located at the point of intersection with the ground. These points are then extruded into a 3D mesh by following a solid angle to and away from the MRO spacecraft, as described in Section 3.2, to fully represent the shape of the spectral pixel.

4.2 Spectral Analysis Tools

The Planetary Visor system equips the user with three interactive tools that further aid in interpreting the data. As discussed in Section 1.3, visualization of multiple datasets poses several challenges. We consulted with planetary scientists to understand the challenges in their field and the current technical state-of-the-art in visualizing and analyzing spectral data. Our discussions found that remote sensing research presents unique visualization challenges. Most importantly, a common observation is that no single technology equips the user with a unified visualization that enables efficient analysis of both orbital and in situ data. Furthermore, current 2D tools present users with challenging interfaces for navigation amidst inherently 3D topographical data. Thus, we began by combining useful tools from existing technologies to provide a multi-scale visualization with intuitive 3D navigation and interactivity with spectral data.

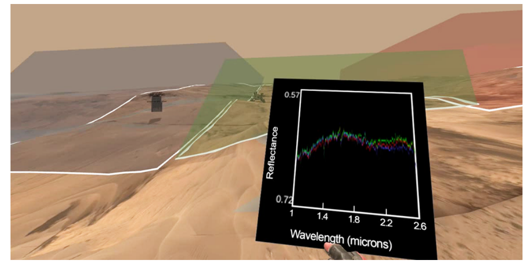

Figure 5: The spectral plotter in VR stays attached to the user's hand which allows for the user to interactively compare spectra as they navigate in situ. The red, green, and blue spectra each correspond to a different PixelBlock in the scene.

4.2.1 Spectral plotting

Analyzing CRISM data requires the ability to interactively view spectra. For Planetary Visor we built a spectral plotting tool, shown in Figure 5, which allows the user to see the spectrum that corresponds to one or more PixelBlocks that intersect with the terrain.

The reflectance values corresponding to a particular pixel are commonly plotted as a function of wavelength. Typically this type of analysis is conducted in 2D on the desktop using GIS such as ENVI or ISIS. Although such programs have built-in sophisticated analysis routines, there is currently no standalone software that allows a user to seamlessly view spectral data on a 3D surface, navigate the terrain, and compare hyperspectral images to one another. Typically the use of multiple simultaneous programs is required to visualize and analyze data from planetary terrains. We built a system that enables the user to compare spectra and terrain, compare selected PixelBlocks and smoothly navigate between different times and scales, in a single scene. Our method of visualization not only reduces the number of applications the user needs, but also provides a better alternative for comparing spectra to the terrain images by bringing everything into a single view.

The spectral plot tool is positioned to stay accessible throughout the experience, enabling the user to view the spectral properties of the terrain as they point at it, without having to look away. In virtual reality, to view the spectral plotter, the user simply lifts up their hand to view the plotter on their wrist. To obtain a clear view of the terrain and its intersection with the pixel, they can lower their hand, naturally moving the spectral plotter out of their field of view. In desktop mode, the spectral plot is locked to a corner of the screen, which can be toggled visible/invisible through a keystroke command.

Additionally, Visor can simultaneously plot multiple spectra corresponding to multiple PixelBlocks. Users can select several areas of the terrain within the scene, which are represented by PixelBlocks of varying colors. The corresponding spectra are then shown on the plotter indicated by the same colors. This allows users to directly compare different spectra interactively.

4.2.2 Region Averaging

Averaging multiple pixels across a region can improve the signal-to-noise ratio of the data. This reduces false-positive mineral detections due to incorrect interpretation of noise as diagnostic absorption features. While existing GIS applications enable averaging across multiple spectra, they lack the ability to transition perspectives between terrain visualization and these calculations. This precludes users from leveraging in-situ terrain information in guiding region selection, e.g., rejecting specific pixels that have artifacts due to topographic shadowing.

We integrate spectral averaging into our visualization with a priority on ease-of-use, while providing valuable views of the data.

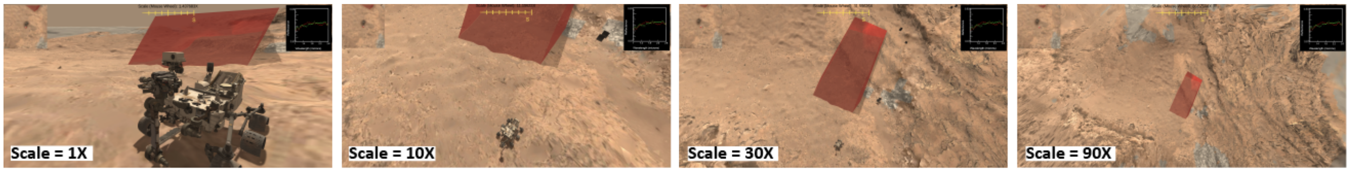

Figure 6: In order to take a contextual view of the terrain and spectral sampling the user can scale themselves up to a large height above ground. To help the user to keep track of where they are, the position of the user stays the same while zooming.

The averaging pixel region is a set of PixelBlocks that has extended functionality. This functionality allows the user to select a region of terrain by dragging their cursor and using a VR controller trigger or mouse click. Visor renders the selected region as a set of PixelBlocks with uniform color. The corresponding color of the averaging pixel region is plotted on the spectral plotter and shows the average spectra for the selected spectral pixels.

The user can customize the size of the region they want and clear the pixels when they are finished with their analysis. The view of the average spectra on the plotter enables efficient comparison of the singular PixelBlocks to the average. This comparison grants relative perspectives of the pixel by showing how that pixel relates to its surrounding pixels and environment. Additionally, the averaging region of PixelBlocks provides the user information about a larger area of interest. This seamless interaction provides an efficient way to conduct the averaging operation, compare pixels, and gain insight about trends across multiple pixels.

4.2.3 Perspective Scaling

An efficient scaling functionality is crucial to bridging the gap between rover perspective and orbital perspective. Visor provides a scaling interaction that lets the user increase or decrease their size, making the terrain appear to shrink or grow respectively. The scaling tool provides natural interactions that help the user make comparisons, increase navigation accessibility and utilize a perspective intermediate between rover and orbiter. We present a visual indicator of the scale factor, which enables the user to track their relative size, as shown in Figure 6.

This feature addresses common issues in traditional 2D visualizations, where the user has difficulty localizing themselves in the larger space while viewing the terrain at 1:1 scale. It has been noted that for many planetary software tools, the loading time of the images after zooming in/out can be quite long in 3D desktop representations. This is due to the way that the programs are developed, where the data outside of the user's field of view is redrawn during zoom operations. Since the view is being reloaded each time, it can be disorienting for users to keep track of their location before and after zooming. This problem makes rapid analysis difficult and potentially confusing.

Our implemented scaling with user interfaces aims to make the scaling interaction feel natural. On desktop, we allow the user to scale their virtual size using the mouse wheel. In VR, we implement a gesture similar to a pinch-to-zoom function on a touch screen; the user holds the controller grip buttons and moves their hands in to scale their size up and moves their hands out to scale their size down. In both versions, we provide the user with a view of their numerical scale, and include a Curiosity rover model in the scene for visual contextual scale.

The scaling tool makes the selecting and viewing of multiple PixelBlocks easier. The PixelBlocks are relatively large when viewed in the environment at 1:1 scale, and it can be difficult to view them all at once, depending on their placement. If the PixelBlocks are scattered around the terrain, the scaling tool allows users to take a perspective that places all PixelBlocks in a single field of view. In such perspectives, users can compare spectral samples of multiple PixelBlocks in different areas.

Larger user scales also bring more area of terrain into the field of view, which naturally widens the range of visible area to move to. For example, if the in situ FOV was blocked by the rocky hills of the terrain, an at-scale user would be forced to navigate over or around it. With scaling capabilities, users can scale themselves up, point a teleportation marker precisely where they'd like to go on the other side of the hill, and move there directly. Thus, Visor's scaling makes navigation more accessible than traditional visualizations, allowing the user to reach the target location with less navigation time and more contextual precision.

5 User Study

Our goal has been to create a tool that is both easy to operate and useful for scientific analysis. To evaluate the degree to which our visualization tool succeeds in these areas, we recruited subject matter experts for a user study. We aimed to answer the following hypotheses:

- H1: The Planetary Visor VR environment increases ease of use and reduces user burden compared to traditional GIS applications.
- H2: The Planetary Visor VR environment increases one's spatial understanding of CRISM data coverage, and pixel intersection with terrain is made clear in VR.
- H3: Planetary scientists find it useful to explore physical aspects of the terrain along with chemical and mineralogical composition.

5.1 Experimental Design

Participants. We recruited participants for our study who work with or have had prior experience with CRISM and/or Curiosity rover datasets. None of our participants were consulted during the development process of the Planetary Visor tool. Our user pool was more limited than we would have preferred due to the circumstances of the coronavirus pandemic. After screening, we selected 8 participants, (3 female, 4 male, 1 agender/non-binary) with ages ranging between 18 - 30. The purpose of the pre-screening was to mitigate any pre-existing conditions that would cause discomfort while using VR headsets. 50% of participants reported that they had used VR before. Participants were compensated with a $10 gift card upon completion of the study.

Procedure. We shipped the participants an Oculus Quest VR headset with a Planetary Visor software pre-loaded. For the purposes of the study, we augmented our software with interactive tasks to guide the user on how to use all parts of our tool. Tasks were displayed inside of the VR headset. Simultaneously, an experimenter was present on video chat to guide participants through the tasks and provide technical support as needed. The videos were recorded for documentation of live user response. In the virtual environment, we placed each user in an area in the Marias Pass region of Gale Crater.

Tasks. The tasks, shown in Table 1, were displayed to the participant sequentially. Each participant was able to complete all tasks.

First, we asked the participants to navigate Marias Pass by pointing their controller at a spot on the terrain in order to teleport to it. Then, we asked them to make various pixel selections and observe the spectral plotter. After they learned how to select new pixels, we showed them the multi pixel block selection tool, so that they could make comparisons. Next, we asked them to plot the average spectra of a region by selection with our averaging pixel tool. Then, we explained our scaling tool, which helped the participants get a better view of their pixel selections. Finally, we asked them to stand at a marked spot on the terrain and look for a yellow sphere. We placed the sphere 30 meters away and asked them to estimate the distance from themselves to the sphere. A true-to-scale model of the Curiosity rover was available for reference.

These tasks were not used to gauge perceptive accuracy – our sample size was too small to yield statistically significant conclusions. Rather, the tasks were designed to run the users through a set of representative tasks to garner meaningful user response.

Metrics. The post-study questionnaire consisted of the following:

- A set of Likert scale questions about participants' ease of use and ability to maintain a sense of scale in Visor compared to traditional tools. (Q1, Q2, Q5, Q6 in Table 2)
- A set of Likert scale questions about perceived CRISM data coverage and the pixel's intersection with the terrain. (Q3, Q4)
- Comparative open-ended questions about user experience in Visor in relation to the participants' unique processes they undertake to conduct spectral analysis.

5.2 User Response

We considered both the participants' live responses to using the tool as well as their responses to the follow-up questionnaire. The questionnaire consisted of the following open-ended questions:

1. Which Planetary GIS software do you use most often?
2. Did you perceive the environment to be similar to a first-person video game, and if so was that useful?
3. Could you potentially see this tool assisting in dissemination and communication of scientific discoveries for planetary data? Can you think of any specific use cases?
4. Was it useful to have the different tools together in your viewer? Would you have preferred for them to be in different locations on the screen?
5. Can you think of any critical tools missing from our system? Are there features we should add that would be helpful in your own work?
6. Did you gain any new perspective from the ability to visualize the shape of a CRISM pixel and its intersection with the 3D surface? Do you think you could potentially acquire any new insights from such a visualization?

The participants' most frequently used GIS software included JMARS, ENVI, ArcGIS/ArcMap, and QGIS. Most participants said that they used combinations of these. Every participant affirmatively responded to question #2 that they did perceive the navigation to be like a first person video game. One participant said that this form of navigation helped them maintain a good sense of scale while roaming around. Another participant said that they perceived the environment to be better than a first-person video game, and found the fluidity and immersion to be very useful to their exploration process. Lastly, one participant verbally stated that the immersion made it easy to navigate, but also remarked that they would have preferred a smooth joystick turn over the snap rotation.

Question #3 asked participants if they could see this tool assisting in dissemination and communication of scientific discoveries for planetary data, and if they could think of any use cases for it. Participants suggested use cases for scientific analysis, education,

Table 1: User study tasks

Task	Description
Navigation	Push joystick forward to teleport, and/or physical navigation via walking and head movement
Pixel manipulation	Dragging/placing, adding, changing color of pixels (reflected on spectral plotter).
Averaging pixels	Select the averaging tool and performing analysis on larger region of terrain.
Scaling	Scale continuously to get new perspectives using the scaling tool.
Distance Estimation	User estimates distance from themselves to a marker 30m away
Explore	Navigate freely with no task, and opportunity for feedback/discussion

Table 2: Likert scale questions and mean responses

Question	Mean
1. Able to maintain a sense of scale with traditional tools	3.5
2. Able to maintain sense of scale with Visor	4.4
3. Able to mentally visualize pixel coverage without software	2.8
4. Pixel coverage and intersection with terrain is made more clear in Visor	3.5
5. Would choose Visor's scaling method over traditional tools to switch perspective	4.4
6. Navigation is natural in Visor, compared to traditional tools with map view	4.0

collaboration and public outreach. One user mentioned that many features and processes observed on other planets are difficult to communicate from orbit due to scaling, but immersion into the data would make it much easier to communicate. Another user mentioned that the 3D view makes the interpretation of features more feasible, because looking at features on a map or an image can sometimes make geologic features hard to interpret. Multiple users mentioned using Planetary Visor as a visual aid at conference presentations. One user gave the use case of taking terrestrial volcanologists on a tour of lava flows on Mars, suspecting they are much longer, thicker, and wider than observed on Earth. Another use case given was to be able to show outcrops with CRISM spectra and APXS data. Additionally, one user said that it can be challenging to show how data from rovers are being used to ground-validate orbital data, but they could see Visor being useful for illustrating this. Lastly, an interesting idea thought of by another user was to remotely send colleagues locations on Mars to investigate.

In response to question #4 regarding the usefulness of the tools Visor provided, participants generally like the placement of the tools and thought they were useful. They had suggestions for tools that would provide additional functionality. About half of the participants suggested some form of a tool menu to encapsulate the tools that are available. One participant mentioned a toggle would be helpful.

Question #5 asked for requests for additional features, and participants offered meaningful suggestions. Two participants noted that a measuring tool could be useful. Half of the participants expressed interest in seeing MAHLI data [13], a feature we are in the process of integrating (§6.2). One user mentioned that it would be beneficial to have a spectral library to compare the CRISM spectra on the fly.

Lastly, we asked the participants if they gained or could potentially gain any new perspective from the ability to visualize the shape of a CRISM pixel and its intersection with the 3D surface. A common response across all participants was that they did gain a new perspective, and more geological context of the data. One user said that the perception of scale is better with the 3D surface, making it easier to understand the area they're studying. Participants had unique examples for how Planetary Visor could assist in answering

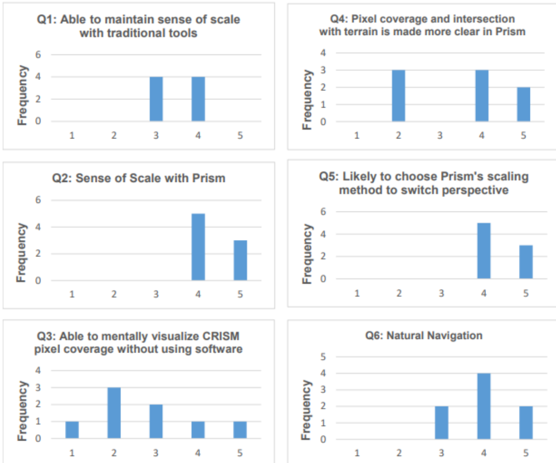

Figure 7: Number of participant responses vs. Likert rating.

some of their questions about Martian geology. One user said that they could correlate the ChemCam data attributed to certain sedimentary features observed on the ground with the CRISM spectrum to see if those features contribute to the overall CRISM spectrum. Another participant said that this sort of visualization is helpful for interpreting photometric effects.

Overall, the participants gave positive feedback about the interface, navigation, and overall experience. Suggestions mostly desired additional datasets and terrain. In summary, participants found the tool to be useful and to potentially bring new scientific insights.

6 Discussion

A main result of our study is that Visor enables users to maintain a sense of scale when exploring physical aspects of the terrain, which in turn increases the ease of use. Responses to the Likert scale questions indicate that participants would be inclined to use the Visor continuous scaling method over their traditional tools. The free response questions and verbal affirmations on video chat confirmed that the scaling mechanism made the terrain easier to navigate and compare spectra.

The responses to the questions regarding spatial understanding and CRISM data coverage suggest that even experts struggle to mentally visualize this area without software. Responses to the Likert scale and open-ended questions indicate that Visor made the spatial understanding and pixel intersection with the terrain clear, improving their geological context for the CRISM spectra. Many participants reiterated this in the free-response section.

Finally, participants found Planetary Visor useful and came up with specific use cases that involve scientific and educational reasons for viewing the terrain with superimposed satellite data. All of the participants indicated that they did or would be able to gain a new perspective with such a visualization.

6.1 Limitations

The Visor tool successfully addresses the main thrusts of our overall goals with this project. However, we have identified limitations and opportunities for expansion and improvement of our tool.

6.1.1 User Study

Due to the circumstances of the coronavirus pandemic, we were unable to gather a large participant pool for our user study. We initially hoped to conduct a portion of our study at a large planetary science conference, which would have significantly grown the pool. Instead, we drew on a small group of planetary scientists to whom we could distribute headsets locally and mailed additional headsets to select experts around the country. We also had to conduct our user studies over video chat rather than in person, which caused us to modify our procedures. Originally, we wanted to users to perform tasks in our lab environment on a typical planetary visualization software such as ENVI or ArcGIS, then on Planetary Visor desktop version, and finally in the VR version. However, to avoid licensing issues and other technical problems, we asked them do the tasks in the Visor VR application only.

6.1.2 Terrain Generation

One of our biggest limitations is that high resolution terrain data is only available along the rover's traverse. This limits the ability to generate terrain meshes, given the number of the Navcam and Mastcam images and the challenges of stitching them together accurately. Remodeling and vertex extraction are often needed for visually cohesive results, which invokes significant time and effort.

Although the HiRISE images and DTM cover far more surface area, the resolution ($\sim$ 25 cm/pixel) is not high enough to support in-situ exploration of the terrain at the scale of the rover.

6.2 Future Works

We plan to add additional CRISM coverage to Visor. Gale Crater has been a frequent target of CRISM observations over the lifetime of the MSL mission. Providing the user with access to multiple CRISM spectra from different observations over the same area increases confidence in mineral detections.

We are also interested in adding additional Curiosity datasets. Users suggested adding MAHLI imagery that supports APXS mission operations. MAHLI images are taken at microscopic scales and give the user insight into the fine-scale sedimentary structure of targets, complementing APXS chemistry and orbital spectral data.

In the future, we would like our application to not only cover the Curiosity rover's current traverse, but those of other NASA missions as well. In July 2020, NASA launched the Mars 2020 Perseverance Rover, which will touch down in astrobiologically relevant site Jezero Crater in February 2021. Extensive CRISM coverage also exists for this site. Many of the instruments and operational procedures on Perseverance are analogous to Curiosity, which would provide similar opportunities to apply Visor.

Additionally, the Visor system can be a flexible tool for use in other planetary science applications. Essentially any geological dataset can be visualized with Visor, such as data from the Earth, Moon, or any other planetary body. Eventually users will be able to upload their own datasets to be visualized with our system.

7 Conclusion

In this work, we present Planetary Visor, a system that integrates satellite and ground imaging data for Mars. We visualize spectral pixels from orbital datasets as spatial intersections of 3D polyhedrons with terrain meshes generated from rover imagery. We have also provided tools for intuitive navigation and efficient scientific analysis. We focus on integrating important components of existing visualization software to make the experience useful, accessible and natural to our users. The qualitative and quantitative results of our user study suggest that our visualization tool provides new perspectives on planetary data and has potential to assist scientists in discovery of new links between rover and orbital spectroscopic data.

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